Four-dimensional (4D) Printing and Its Applications

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Abstract

Four-dimensional (4D) printing is one of the emerging technologies. The fourth dimension in 4D printing refers to the ability of 3D printed material objects to alter its geometric configuration from one to another in a fully controllable manner, thus providing additional functional capabilities and performance-driven applications [1, 2]. With the additional dimension, 4D printing is emerging as a novel technique to enable configuration switching in 3D printed items. The purpose of this paper is to briefly discuss the 4D printing and to review some applications to demonstrate the potential of 4D printing.

Introduction

4D is based on 3D printing technology, but requires additional stimulus and stimulus-responsive materials. Three key capabilities of this technology are the machine, the smart material and the mathematical modeling. Smart materials are materials that produce a change in shape or property (e.g. rigidity, color, texture, transparency, volume) when exposed to an external stimulus. Shape memory alloys (SMAs), for example, are a popular smart material that possess two phases allowing SMAs to alter shape and return to its original shape when exposed to high temperatures. Shape memory polymers (SMPs), another class of smart materials that are gaining popularity, possess the ability to remember a permanent shape and transform to a temporary shape when exposed to several external stimuli such as temperature pressure, water, PH-levels, or light. Mathematical modeling is required for the design of the distribution of multiple materials in the structure. There are at least two stable states in a 4D printed structure, and the structure can shift from one state to another under the corresponding stimulus. Based on certain interaction mechanisms between the stimulus and smart materials, together with appropriate design of multi-material structures from mathematical modeling, 4D printed structures have the ability of transformation by embedding a program directly into the materials by themselves [3, 4, 5, 6]. According to a new report by Grand View Research, 4D printing may find applications in the automotive, textiles, construction, healthcare, utility, aerospace, and military industries. The market report also predicts that the global 4D printing market is expected to reach $313.1 million by 2025 [7, 8].

Smart Materials

Smart materials are defined as those materials have the capability to transform their geometry when exposed to an external stimulus [6, 9, 10, 11]. Some well-known smart materials such as shape memory alloys (SMAs), shape memory polymers (SMPs), hydrogels, light-responsive materials, and bio-materials were discussed as follows.

Shape Memory Alloys (SMAs)

Shape memory alloy (SMA) is one of temperature-responsive materials that possesses two phases: martensite phase (low temperature) and austenite phase (high temperature). The shape memory effect (SME) is a result of the transformation between two different crystalline phases in the SMAs. When the SMA is deformed in the low temperature phase, followed by heating the alloy above a critical temperature, a reverse phase transformation can be induced. The initial shape of the deformed alloy will be restored as the crystalline structure transforms from low temperature phase back to high temperature phase [6, 7, 8, 11, 12].

SMA is elasticity, whereby the alloy demonstrates a large recoverable strain upon loading and unloading. One example of SMAs that can exhibit both SME (thermal memory) and super elasticity (mechanical memory) is the Nitinol, a SMA with a composition of nickel (Ni) and titanium (Ti) developed at the Naval Ordinance Lab. The transformation temperatures are very sensitive to the variation in the Ni/Ti ratio. A slight drop in the Ni content can lead to a huge increase in the transformation temperatures. Nitinol SMAs can be found in automotive, aerospace, biomedical, robotics, and soft actuation industries [6, 11].

Shape Memory Polymers (SMPs)

Another class of smart materials that are gaining popularity are shape memory polymers (SMPs). SMPs can be programmed to memorize a predetermined shape and transform to a temporary shape when exposed to a number of external stimuli such as temperature, pressure, water, pH-levels, magnetic fields, or light [1, 11]. SMPs offer a relatively stiff structure and fast shape-shifting. Compared to the SMAs, SMPs have some advantages such as high strain recovery, lower density, lower cost, simple procedure for programming of shapes, and good controllability over the recovery temperature. SMPs can also be modified chemically to achieve biocompatibility and biodegradability. However, their major drawbacks include low strength, low moduli, and low operating temperature [6, 11, 13]. SMPs require complex process to make the printed material. After the SMPs are 3D-printed, they must undergo thermomechanical programming, which involves heating, mechanical loading, cooling, and load removal [13].

Hydrogels

For 4D-printed component based on hydrogels, the hydrogel is combined with a non-swelling polymer. When the printed structure is immersed in a solvent, the hydrogel swells while the non-swelling polymer does not, creating mismatched strains between the two materials that cause the component to change shape. This approach is simple and does not require programming. However, hydrogels are soft so that the printed object typically lacks stiffness that is needed in many applications. In addition, the change happens very slowly because the shape-shift is based on diffusion. Also, the actuated shape is not stable and will changes as the environmental conditions change [13].

Light-responsive materials

Light-responsive materials can also be used as 4D printing materials. UV light energy induces the deformation of the UV responsive polymer chain structure, triggering a color change caused by a shift in the polymeric chain from the ordered nematic phase to the disordered phase. These light-responsive materials can be used in shopping bag packaging, aerospace structures, photovoltaics, and biomedical devices. Its applications also can be found in the fashion and entertainment industries [9].

Bio-materials

Bio-materials are a major class of smart materials for 4D printing. Typically, biocompatible materials should degrade in the body environment within a certain period of time. 4D printed body parts or structures should have dynamic functional behaviors for use in vivo. Well-known self-degrading materials include polylactic acid (PLA) and poly-caprolactone (PCL). Both materials have been reported to degrade over a period of several years until the polymer chain has completely dissolved in body fluid [9].

One category of 4D bio-printing is laser-assisted bio-printing. The high resolution of this technique allows more details and information to be integrated into the tissues to create tissues with high complexity. According to Khoo et al. (2015), the fourth dimension of this laser-assisted bio-printing technique is the time dimension that is related to the self-organization of the cellular processes such as cell communication and cell interaction. Another category of 4D bio-printing is the 3D printing of smart hydrogels. Smart hydrogels possess the ability to respond to external stimulus such as electric, ionic strength, light, magnetic field, pH and temperature. They have unique features such as shape memory, self-healing and controllable sol–gel transition. By using the potential of 3D printing to fabricate structures made of smart hydrogels, the fabricated 4D bio-printed structures or bio-origami hydrogel scaffolds can have the capability to self-fold or self-unfold in response to external stimulus. This will help to contribute to the area of bio-printing of functional 3D tissues [11].

The Design of 4D Printed Structures

In 3D printing, the printer builds an object layer by layer to create a rigid, static object. In 4D printing, which incorporates programmable materials into the printed object, the code for the virtual blueprint includes a precise geometric mapping element based on the object's angles and dimensions that determines how it will change shape in the presence of an external stimuli. This additional code determines how the responsive material is incorporated into the final, printed object [4, 9].

Project Cyborg, an application was embedded into the Autodesk software, is an example of a simulation software that has been used by researchers to determine how and when the various components will behave during the self-assembly process [14]. Project Cyborg allows for specific areas of a part to be assigned with the smart material properties and provide a visualization of the object’s bending process [6, 11, 12]. Kinematics is another 4D printing software that was developed by Nervous System. Kinematics takes custom objects and folds the design into a compact shape that can be 3D printed in a single run. The software has been used for 4D printing clothing because of its advanced folding algorithm. 4D printing software still requires further research and development for different activation methods of the smart materials [6].

Printers for 4D printing

The printing of multi-material components is a key factor for the 4D printing of structures with adaptability and desired functionalities. Multi-material printers allow printed structures to have colors, shapes, or electronic properties that change in response to UV rays, light, heat, or water. Multi-material printers can print functionally graded structures by mixing two or three different materials within one printed structure [9]. Polyjet printer from Stratasys is the most established technology in performing multi-material printing. Most of the developments in 4D printing utilize PolyJet printers in their research to fabricate multi-material components that consist of smart materials and conventional materials. Polyjet printing dispenses the liquid material on a layer-by-layer basis and cures each layer using UV light. Other 3D printing technologies such as fused deposition modeling (FDM), selective laser sintering (SLS), and stereolithography are future processes that could be used in 4D printing technology; however, some 4D printing technologies may require multi-materials and multiple nozzles, which limits what 3D printing methods can be used. Exploring different printing methods can allow for different smart materials to be 3D printed that are stronger, lighter, induce different property changes, and react to different stimuli [6].

Examples of 4D Printing Applications

Although 4D printing is still in its early development stage, 4D Printing and programmable active materials offer exciting opportunities for the future of the products. Real-world applications of 4D printing have been developed for potential use such as for functional textiles, smart products, adaptive biomedical devices, and interactive electronic apparatuses [1]. Below review are several examples of 4D printing and potential applications.

Product Design

Tolley et al. (2013) fabricated self-deployable systems (SDSs) by using additive laser manufacturing (ALM) technology with SMP materials. They use the ALM technology to combine the SMP material and hard matrix material into an intelligent structure, which can realize self-assembly and self-folding under external environmental stimulus. One of the most famous applications in detectors is the Inchworm Robot (Fig. 1). By controlling the repeated bending and folding of the Inchworm Robot, its progressive motion can be realized [12].

Engineers from MIT and Singapore University of Technology and Design (SUTD) developed a SMP-based thermo-responsive multi-material gripper [5], as shown in Fig. 2.

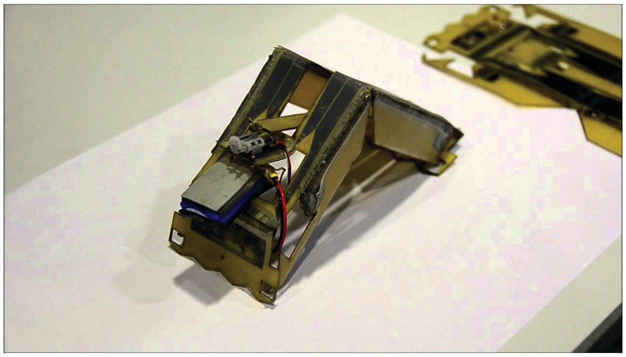

Fig. 1. 4D printed Inchworm Robot.
Source: https://www.youtube.com/watch?v=03C6GA__onw

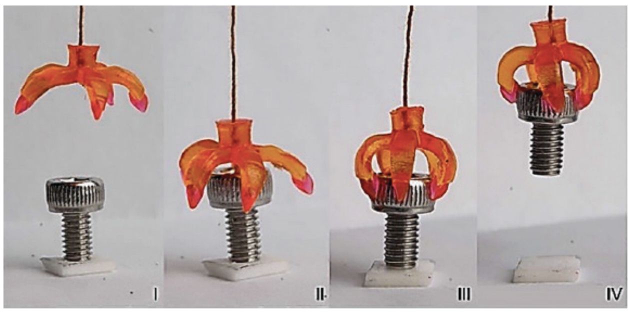

Fig. 2. 4D-printed shape memory gripper that can reversibly grab and release the objects by heat.
Source: https://www.sculpteo.com/blog/2016/09/28/top-10-future-3d-printing-materials-that-exist-in-the-present/

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In the future, the advanced manufacturing sector could see major benefits of using 4D printing by reducing the number of assembly parts, reducing required resources, and easier transportation of products. Imaging that parts can be 3D printed in flat compact shapes for easy transportation and shipping; next, a source of energy could transform the object into a desk, chair, or storage unit when it reaches its destination. This process may be able to work reversely; if users are relocating, the product could be activated to change into a more compact shape for transportation [6].

4D Printing Textile Applications

4D printing may be applied to textiles and camouflage technology by altering not just color and patterns, but also altering the texture of the surface. Smart materials could be 3D printed onto textiles and alter the shape and rigidity of the clothing to give a textured look in changing environments. Camouflage could react to different weather effects and change dynamically according to the environment. Clothing could react to the environment's temperature or the wearer's body temperature allowing ventilation or insulation for dynamic cooling and heating [6].

4D printing textile applications could be embedding the smart material into the fibre and 3D printing the fibre into desired shapes. Layers of cloth with adhesive are dispensed on top of each other on a layer-by-layer basis. Each layer of the cloth is cut with a laser in the shape of the object. The outer layer of the cloth can be removed when the printing process is completed. Researchers in the self-assembly lab at MIT print smart materials in varied layer thicknesses onto stretched textiles to create self-transforming structures that reconfigure into pre-programmed shapes (Fig. 3). Programmable textiles provide possibilities for furniture, product manufacturing, and shipping.

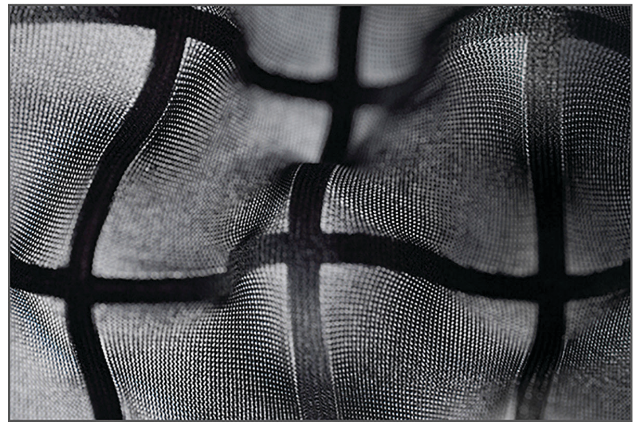

Fig. 3. 4D-printed programmable textiles
Source:
http://www.selfassemblylab.net/ProgrammableMaterials.php

Another method is 4D printing intelligent parts and integrating them with textiles after post processing. Initially, smart textiles may find applications in the medical field, space exploration, and military; however, once these applications are concrete then they may transfer over to the sports and casual fashion industries [6].

Self-adaptive and multi-functional textiles are some of the potential applications that can be improved by 4D printing. Self-adaptive smart textile structure can be adapted to a new size without tensile loading, in contrast to the textiles made of elastic fibers. Multifunctional smart textiles are able to manage the moisture or temperature of the body, monitoring wounds, providing skin care, protecting against harsh climates, or adaptively changing color of a dress [5].

Biomedical Applications of 4D Bio-printing

One example of biomedical applications is polylactic acid (PLA) surgical staple (Fig. 4). FDA approved PLA is a biodegradable material for implanted medical devices. PLA surgical staples have been used as an alternative to biodegradable sutures in minimally invasive surgery for wound closure. The PLA staple has the self-tightening function upon heating to slightly above body temperature. Since the actuation stress of PLA during shape recovery is not high, over-tightening can be effectively avoided [2].

4D printing technique will expand the application of shape memory-exhibiting biomedical devices to many different clinical indications and converges with the zeitgeist of personalized medicine. For example, 4D printed stent (Fig. 4) can be printed, deformed into its temporary shape, inserted in the body and then deployed back into its permanent shape with a local increase in temperature. 4D printed stent better matches the arcade-like geometry of the trachea and currently is used for airways, which is expected to improve the prognosis for those requiring an airway stent [15].

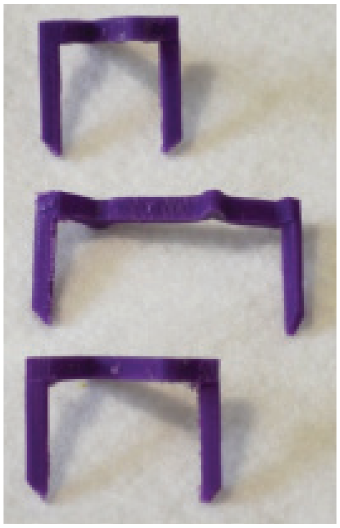

Fig. 4. Biodegradable PLA staple with self-tightening function. Top: as printed shape; middle: after programming; bottom: after heating for shape recovery
Source: Ye Zhou et al. (2015), From 3D to 4D printing: approaches and typical applications, Journal of Mechanical Science and Technology. 29 (10), p. 4285.

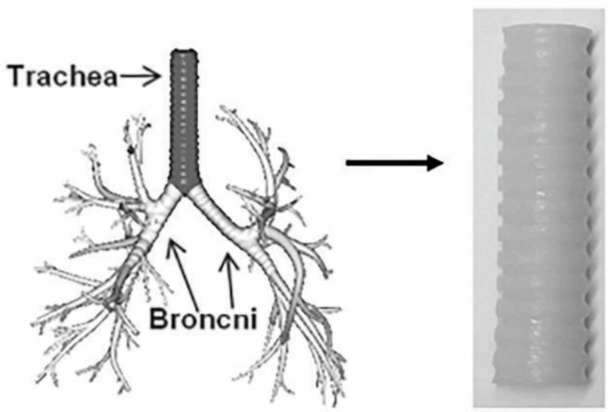

Fig. 4. shape memory airway stent.
Source: Matt Zarek et al. (2017). 4D Printing of Shape Memory-Based Personalized Endoluminal Medical Devices. Macromolecular Rapid Communications. 2017, 38:2, 1600628.

4D bio-printing could become a major advancement in the design and application of bio-scaffolds and biomedical devices. Bin Gao at al. (2016) state that cell diffusion and cell density throughout the volume of the scaffolds remains inconsistent and limited near the center of the scaffold. One solution is the 4D printing of scaffolds in a flat plane, seed the cells, and transform the scaffold into its final shape [6, 16]. The issue of combining 4D printing and bio-printing is the biological compatibility of many different SMPs has not been tested. Also, their reaction stimuli that causes their shape change would have to be safe for the biological body and easily controllable [6].

Conclusions

Recently, 4D printing has been gaining attention because its structures have the capability to change in form or function over time in response to stimuli such as pressure, temperature, water, and light. Indeed, 4D printing technology is a relatively new research area and its application in smart material structure are still in initial stage. 4D printing has a lot of challenges ahead. There are still several research subjects to overcome three limitations: process, material, and design. However; advance in new materials, printing methods, software, and machines will have a profound impact on the traditional mechanical structure design and manufacturing and make 4D printing a more realistic and accessible technology.

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